NASA/TM-2003-210741

The Active Aeroelastic Wing Phase I Flight Research Through January 2003

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April 2003

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April 2003

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ABSTRACT

This report describes the technical content of the Active Aeroelastic Wing (AAW) Flight Research Program and discusses the analytical development, aircraft test bed modifications, ground test results, and flight research results through January 2003. The goals of the AAW Flight Research Program are to demonstrate, in full scale, AAW technology, and to measure the aerodynamic, structural, and flight control characteristics associated with the AAW aircraft. Design guidance, derived from the results of this benchmark flight program, will be provided for implementation on future aircraft designs.

NOMENCLATURE

AAW	Active Aeroelastic Wing
ABUC	aft box upper covers
AFRL	Air Force Research Laboratory
Al	aluminum
ASE	aeroservoelastic
CM	control module
cmp	composite
FCC	flight control computer
FCF	functional check flights
FCS	flight control system
FEM	finite-element model
FI	flexibility increment
GVT	ground vibration test
HARV	high alpha research vehicle
ITB	integrated test block
LEF	leading edge flap
LEFDS	leading edge flap drive system
NASA	National Aeronautics and Space Administration
OBES	onboard excitation system
PID	parameter identification
PDU	power drive unit
RAM	random access memory
RFCS	research flight control system
SMI	structural mode interaction
TEF	trailing edge flap
Ti	titanium

INTRODUCTION

The Active Aeroelastic Wing (AAW) technology[1,2] is a multidisciplinary technology that integrates air vehicle aerodynamics, active controls, and structural aeroelastic behavior to maximize air vehicle performance. The concept uses wing aeroelastic flexibility for a net benefit and enables the use of wings that are aeroelastically deformed into shapes for optimal performance. This design allows the achievement of the multipoint aerodynamic performance required of future fighter,[3] bomber, and transport aircraft.

The AAW technology employs wing aeroelastic flexibility for a net benefit through use of multiple leading and trailing edge control surfaces activated by a digital flight control system (FCS). At high dynamic pressures, AAW control surfaces are used as tabs that are deflected into the airstream in a manner that produces favorable wing twist. Conventional use of control surfaces can result in reduced control associated with aileron reversal caused by trailing edge surfaces. The AAW technology uses the energy of the airstream to twist the wing with very little control surface motion. The wing itself creates the control forces.

As AAW technology attempts to promote and use favorable wing twist response at high speeds, the concept is viewed as a return to an idea first pioneered by the Wright Brothers.[4] Overall benefits of AAW technology to future systems include substantially increased control power, reduced aerodynamic drag, reduced aircraft structural weight, and increased design latitude in terms of wingspan, sweep, and thickness. Depending on mission requirements, these benefits should significantly reduce air vehicle takeoff gross weight and production costs.[5]

This report discusses the AAW background and program development, including the modifications that were made to the F/A-18 aircraft and the ensuing structural testing. A detailed outline of the phase I flight test program and results to date will be discussed.

BACKGROUND

The goal of the AAW Flight Research Program is to validate a vehicle concept in which a lighter, more flexible wing is used to improve overall aircraft performance. The AAW design philosophy sharply contrasts with conventional design practice in which wing flexibility is avoided at the cost of added structural weight. During several wind-tunnel test programs conducted from 1984 to 1993, AAW technology has been shown to provide large amounts of control power across the aircraft envelope.[6,7] This control power can be used to twist and camber the wing into shapes that minimize drag at multiple flight conditions; reduce structural loads; and provide control for rolling or pitching the air vehicle.

The AAW technology can be applied to high-performance aircraft, which are required to operate in a broad range of subsonic, transonic, and supersonic conditions. During design studies, AAW design techniques have been applied to several fighter concepts and have been shown to reduce aircraft takeoff gross weight by 5 to 20 percent.[3,8]

In 1996, a joint flight research program, involving the Air Force, NASA, Navy, and industry, was initiated to demonstrate AAW technology using a full-scale F/A-18 fighter aircraft (fig. 1). The F/A-18 aircraft is an ideal choice for AAW technology demonstration, because of the high-speed flight capability and the thin, flexible wing with multiple control surfaces, which together produce aeroelastic characteristics that can be exploited by the application of AAW technology. The Boeing Company (Boeing Phantom Works, St. Louis, Missouri), under contracts with the Air Force Research Laboratory (AFRL) Air Vehicles Directorate (Wright-Patterson Air Force Base, Dayton, Ohio) and the NASA Dryden Flight Research Center (Edwards, California), modified the AAW F/A-18 research aircraft.

The flight research program was initiated to flight-test some of the characteristics of AAW technology. The goal of the program is to develop full-scale flight data that demonstrate and measure the physics of AAW technology in a low-cost, effective manner. Full-scale flight testing of AAW technology will evaluate the effects of full-scale Reynolds numbers, Mach numbers, angles of attack, and elevated aircraft maneuver accelerations. Both ground and flight tests evaluate the effects of wing stiffness, wing aeroelastic hysteresis, actuation responses, and actuation hysteresis and lags. The flight research program will provide benchmark design criteria to guide future aircraft designs.

F/A-18 AIRCRAFT MODIFICATIONS

The AAW design philosophy used for the aircraft modifications provides wing structure for strength, buckling, and flutter constraints, but does not add structure to satisfy typical stiffness constraints for roll effectiveness. A high-rate actuation system was required for the leading edge control surfaces to help exploit the modified structural stiffness. The AAW program started with an F/A-18 aircraft that had been used for the high alpha research vehicle (HARV),[9] and several modifications to the aircraft were made. The wing skin panels were changed to increase aircraft flexibility. A leading edge flap drive system (LEFDS) was added that controls an independent outboard and inboard leading edge flap (LEF). The flight control computer (FCC) hardware and software were modified. Finally, a research instrumentation system was designed and added to the aircraft to monitor and evaluate the aircraft dynamics and loads.

Wing Modifications

The wing modification goal was to reduce the torsional stiffness characteristics of the AAW aircraft from that of the standard F/A-18 aircraft. This goal was accomplished by removing the aft upper and lower wing surface cover panels and replacing them with a more flexible set. Figure 2 shows the location of the panels. The original aircraft panel configuration (fig. 3) had three panels on both the upper and lower wing surfaces inboard of the wing fold. Outboard of the wing fold, the upper wing surface had one panel and the lower wing surface had two panels. These panels were made of aluminum (Al), titanium (Ti), and a solid composite (cmp) skin.

Figure 4 shows the modified AAW aircraft wing panel configuration. On the upper wing surface, inboard of the wing fold, five panels made of aluminum and thinner composite skins with honeycomb substructure replaced the three panels. Outboard of the wingfold, two thinner aluminum panels and one thinner composite skin replaced the one solid composite panel.

On the lower wing surface, the most inboard titanium panel was not replaced. The solid composite panel inboard of the wing fold was replaced with a thinner composite skin with a honeycomb substructure. The titanium panel just inboard of the wing fold was replaced with a thinner aluminum panel. The two outboard panels were replaced with two thinner aluminum panels and one thinner composite panel. The wing panel modification removed approximately 67 lb from the aircraft wing. The stiffness test results, which are discussed in the “Aircraft Analysis and Testing” section of this report, show the increase in torsional flexibility from the analytical predictions.

Leading Edge Flap Drive System (LEFDS) Modifications

The basic F/A-18 aircraft model used for the AAW program has an LEFDS that controls the inboard and outboard LEFs as one unit. The modified AAW LEFDS controls the inboard flap independently of the outboard. The independent flaps allow the AAW control laws a greater ability to use the wing flexibility in controlling the aircraft.

Some of the new features of the AAW LEFDS are the new power drive unit (PDU) and control module (CM) (fig. 5). The PDU provides rotational motion to the flaps, while the CM controls the hydraulic flow to the PDU. Both the PDU and CM were developed from newer models of the F/A-18 aircraft. The LEFDS transmissions convert from high speed–low torque to low speed–high torque to drive the LEFs. The inboard transmission and torque limiter were not modified from the original aircraft. The outboard transmission was added to independently control the outboard LEF.

The new LEFDS hydraulic system and electrical system were also modified. The hydraulic system had used larger supply and return lines to the wings; therefore, new lines to the LEFDS PDUs were added. The new lines tap into the existing F/A-18 hydraulic circuits. The electrical system modifications include the addition of new wiring to the LEFDS on the front spar and the addition of wiring to the FCCs and cockpit displays. When possible, existing wiring was used for the new LEFDS. The new LEFDS along with the hydraulic and electrical modifications added approximately 70 lb to the aircraft wings.

Flight Control Computer (FCC) Modifications

Two sets of F/A-18 aircraft FCCs were modified for the AAW program. These modifications include the addition of a new analog board to drive the outboard LEF surface, and the incorporation of a faster processor for AAW flight research software.

The basic F/A-18 FCS consists of quadruplex redundant computers.[10] The computer was modified for the AAW aircraft by adding an analog interface for the LEFDS actuators, and a research flight control system (RFCS). Figure 6 shows the F/A-18 AAW computer architecture. The analog input card and RFCS were added to spare card slots in the basic FCC. The standard processor runs the baseline F/A-18 flight control laws and computes control surface commands to all control surfaces, including the new outboard LEF. This basic FCC maintains control of the aircraft; manages the actuator signal input and output; communicates with the F/A-18 mission computer for outer loop control; and displays information through a Military Standard 1553 Data Bus. The RFCS, which provides a flexible system for control law research, communicates to the basic FCC through the dual port random access memory (RAM). The RFCS has no direct control of the aircraft and is called only during the research portions of the AAW flight. The RFCS processor is engaged by means of a cockpit switch.[10] The pilot selects a preprogrammed maneuver from the upfront cockpit display, and then engages or activates the RFCS by selecting a button on the control stick. When the RFCS is engaged during the first phase of flights, actuator commands computed by the RFCS are added to the commands from the aircraft baseline FCC.

The software program of the research actuator commands is called the onboard excitation system (OBES). The first phase of flights has 31 separate OBES maneuvers programmed into the RFCS. The OBES maneuvers include maneuvers for aeroelastic model validation and maneuvers designed to deflect aircraft control surfaces individually so that loads and aerodynamic model validations may be extracted from aircraft measurements. The model validation part of the OBES is referred to as the OBES parameter identification (PID). When the RFCS is disengaged because of pilot input or a system fault, transition logic reverts flight control back to the baseline FCC and the baseline flight control laws.

Flight Controls Modification

The baseline F/A-18 control laws command the outboard LEF actuators to the same positions as the inboard LEF actuators. In the RFCS mode, the outboard and inboard LEFs act independently. The aileron and outboard LEF control surfaces are assumed to have the most significant effect on controlling wing flexibility.[2] To exploit this anticipated effectiveness, the outboard LEF performance was increased with the new AAW LEFDS. Table 1 shows the performance characteristic of all the control surfaces. Each control surface has the same rate and travel in the baseline and RFCS modes, except for the outboard LEF. The outboard LEF, when used in the RFCS mode, has increased travel and rate. The travel increases 7 degrees upward and the rate increases 300 percent from 15 to 45 deg/sec. The increases in actuator performance allow greater flexibility for collective biasing of the LEF commands for acquiring PID data during flight tests. Since this limit applies to AAW commands from the RFCS, this change also allows greater flexibility for designing the AAW control laws.

Table 1. Control surface performance characteristics.

Control Surface	Rate, Deg/sec	Upward Travel, Deg	Downward Travel, Deg
Aileron	100	25	45
Inboard LEF	15	3	34
Trailing Edge Flaps	18	18	45
Stabilator	40	10.5	24
Rudder	56	30 (left)	30 (right)
Baseline outboard LEF	15	3	34
RFCS outboard LEF	45	10	34

Research Instrumentation Modification

The AAW has an extensive research instrumentation system. The system consists of more than 1600 independent parameters that research engineers can monitor during ground and flight tests and use in analysis. Figure 7 shows the distribution of the sensors and other aircraft measurements. The sensors include nearly 200 full strain gage bridges that are used in monitoring control surface hinge moments and wing root and fold loads. Sixteen flight deflection sensors are used to measure wing displacement and twist to correlate with the loads data, which in turn is used in AAW technology development. Fifty dynamic accelerometers are used for flight flutter testing and aircraft structural dynamics research. Two sensors on each control surface measure position, in addition to the standard aircraft position sensors. Included in the instrumentation package are temperatures, control surface commands from the flight computers, and accelerometers that measure the aircraft dynamics such as roll, pitch, and yaw. Many more aircraft health-monitoring measurements are available from the aircraft mission computer. Future instrumentation will include unsteady pressure measurements behind the LEF outboard of the wing fold.

Each sensor or measurement on the aircraft has its own signal conditioning and has been tested end to end. Calibration of each sensor was completed either in the laboratory or on the aircraft.

AIRCRAFT ANALYSIS AND TESTING

The AAW aircraft analysis and testing consisted of structural loads testing, including wing torsional stiffness and loads calibration tests; structural analysis; ground vibration tests (GVTs); and structural mode interaction testing. This section describes these analyses and tests in detail.

Structural Loads Testing

Two wing torsional stiffness tests were performed on the AAW aircraft wing to provide data on the torsional flexibility characteristics. A loads calibration test was completed to use the strain gages in load equations for control surface hinge moments and wing bending, torque, and shear.

To establish a baseline on the wing flexibility, in November 1996 a preliminary wing torsional stiffness test was conducted on the left wing of the F/A-18 test bed aircraft. In April 2001 following completion of wing stiffness modifications, a second wing torsional stiffness test was conducted to establish the modified torsional stiffness characteristics of the AAW research aircraft. These tests simulated approximately 70 percent of the structural flight limit load. The loads were applied by means of hydraulic cylinders to the load fixtures (fig. 8). These tests were accomplished at NASA Dryden, and the details of the tests can be found in reference 11. The results are summarized in the following section.

Figure 9 shows the torsional stiffness results obtained by the AAW aircraft wing modification in terms of flexibility increment (FI). The FI is a percentage defined as the portion of the flexibility increase obtained from removing the aft box upper covers (ABUCs). Removing the ABUCs represents the 100-percent FI. The 0-percent FI is represented in figure 9 as “ABUCs fully effective,” as analytically determined. The dashed line represents the AAW predictions of where the FI is for the AAW modified wing. This figure shows that the AAW predictions closely match the flexibility of the tested AAW aircraft wing outboard of the wing fold. The AAW aircraft wing modifications did not, however, reduce the wing stiffness as much as was first expected when compared to the baseline test results. Wing stiffness was not reduced as much as was first expected, because the AAW aircraft wings were previously flown and had experienced wear, resulting in increased slippage between fasteners, wing panels, and the wing substructure. This slippage was reduced during AAW aircraft refurbishment, because new bolt and hole tolerances were manufactured for the AAW program. Overall the AAW aircraft achieved a reduction in wing stiffness of approximately 5 percent from that of the baseline F/A-18 wings (with wear). The AAW aircraft achieved a reduction in wing stiffness of approximately 17 percent from that of the baseline F/A-18 wings with no flight wear. Both the 1996 and 2001 results show an unpredicted nonlinear drop in flexibility near the wing fold that might be caused by the wing fold mechanism. The modification goal was to return the stiffness to a level similar to that of the early prototype F/A-18 wings. This goal was achieved, and an adequate stiffness level was achieved to demonstrate AAW technology.

In November 2001 at NASA Dryden, a complete loads calibration test was conducted on the AAW aircraft.[12] Figure 10 shows the aircraft undergoing loads calibration testing. The figure shows images of the wings at different load conditions superimposed upon each other. The primary objective of the loads calibration test was to obtain calibration data from 200 strain gage bridges (installed on AAW F/A-18 aircraft) during the application of single-point and distributed loads. For measurement system comparisons, the strain gage data was correlated with data from the flight deflection measurements and ground deflection potentiometers.

Load equations were developed for left and right wing root and fold shear, bending moment, and torque; and load equations were also developed for all eight wing control surface hinge moments. Thirty-two hydraulic jacks with whiffle trees were used to apply loads through 104 tension and compression load pads bonded to the lower surfaces of the wings. A series of 72 load cases was performed including single-point, double-point, and distributed load cases. Applied loads reached 70 percent of structural flight limit load. Primary and multiple backup load equations were developed for each of the 20 wing component loads using a least-squares regression analysis program. Loads calculated from strain gage outputs were compared with aggregate applied loads, and these load results showed good agreement. These equations were implemented in the control room and monitored in real time during flights.

Structural Analysis

As part of the design process, Boeing and NASA developed corrections to baseline F/A-18 databases for aerodynamics, structures, and control surface models, to account for the increase in wing flexibility. An AAW F/A-18 finite-element model (FEM) was created to analyze and assess the effects of the modifications on wing stiffness. The AAW FEM was updated based upon results of the wing stiffness tests. The FEM was derived from geometry and stiffness properties obtained from the Boeing F/A-18 detailed stress model, and from mass properties obtained from the F/A-18 beam rod flutter model. Figure 11 shows the FEM, which consists of approximately 854 nodes, 2418 elements, and 191 rigid elements. The 2418 elements include point, quadrilateral, and bar elements.[12]

The FEM was used to conduct preliminary flutter analyses, which projected flutter velocities to be outside the AAW F/A-18 test bed envelope with margins exceeding 15 percent. The predicted flutter mechanism, a coupling between the wing first-bending and first-torsion modes, agrees well with previous flutter studies. To ensure that the test bed design modifications considered all technical and safety issues, the FEM was also used to conduct a number of additional analyses, including aerodynamic, aeroelastic control power, vibration, structural integrity, design loads, loading conditions, and stress analyses.

Ground Vibration Tests (GVTs)

The GVTs are performed to assess the structural characteristics of new and modified research vehicles.[13] The results of the AAW GVT were used to verify that structural modifications to the aircraft were correctly modeled. The analytical model was then updated for flutter analysis. Only two aircraft configurations, empty fuel and full fuel, both with gear up, were required for validation of the analytical model.

During the GVT, the aircraft was on a soft support system (fig. 12), which supported the aircraft at the jacking points. Standard aircraft jacks were required to retract the landing gear. An overhead hoist lifted the aircraft for installation and removal on the soft support system. The soft support system simulates the free-flight configuration of the aircraft and acts to isolate the rigid-body modes from the elastic-structural modes. The aircraft was in a flight configuration with the gear up and the control surfaces in a nulled position.

The wings were excited by means of two 150-lb shakers. The shakers were located on the outer torque boxes at the intersections of the spar and rib, along the leading edge of the right wing, and along the trailing edge of the left wing. A third shaker was attached to the left horizontal stabilator. A burst random excitation was used to get a broadband response from the airplane. Increased force levels were used to check for nonlinearity.

The lowest burst random excitation force level (2.6 lb rms) identified as many as 19 analytical modes to a maximum of 30 Hz and gave the cleanest mode shape results. The first eleven GVT mode shapes from 6 to 20 Hz, shown in table 2, match the analytical mode shapes to within 10 percent.

Table 2. AAW GVT modal frequencies compared with analytical predictions.

Analytical Frequency (Hz)	GVT Frequency (Hz)	Percent Error	GVT Mode Shape Description
5.97	6.241	4.53	Symmetric wing first-bending
8.85	8.325	–5.93	Antisymmetric wing first-bending
9.00	8.689	–3.46	Antisymmetric wing first-bending, fuselage rotation
9.34	9.872	5.70	Fuselage first-bending
13.54	13.015	–3.88	Antisymmetric stabilator first-bending
13.61	13.490	–0.88	Symmetric stabilator first-bending
14.10	14.534	3.08	Symmetric wing first-torsion
14.16	15.626	10.35	Antisymmetric wing first-torsion
15.71	15.824	0.73	Antisymmetric vertical tail bending
15.92	16.279	2.25	Symmetric vertical tail bending
17.74	16.891	–4.78	Symmetric wing second-bending

Structural Mode Interaction Testing

Structural mode interaction (SMI) testing was completed on the AAW to verify that the structural changes to the AAW aircraft do not adversely interact with the digital FCS. The objectives of the testing were to obtain responses and transfer functions that define the dynamics of the airframe and actuators, and to determine any dynamic coupling between the airframe and the FCS sensors and actuators. Another objective was to obtain data that can be used to validate analytical aeroservoelastic (ASE) analysis results. The most important objective was to ensure that the servoelastic gains met safety requirements.

The SMI tests were also conducted with the aircraft on the soft support system. The FCS was activated, and a series of OBES maneuvers, consisting of six Schroeder inputs,[14] was run. The Schroeder input, a combination of many sine wave signals of varying frequencies, was 35 seconds in duration for the AAW SMI test. Figure 13 shows a sample OBES Schroeder command signal. The six inputs consisted of a symmetric sweep to the ailerons, outboard LEFs, stabilators, and rudders. In addition, an antisymmetric sweep was sent to the ailerons and outboard LEFs.

The SMI test demonstrated that the AAW aircraft had a sufficient gain margin by increasing the loop games in the feedback loop. The test also demonstrated that no adverse interaction exists between the control system and the aircraft structure. Further analysis of the SMI data is currently being conducted, along with correlation between the SMI and flight data.[15]

FLIGHT RESEARCH APPROACH

The core AAW flight research testing has been planned in two phases that ensure a safe, thorough evaluation. Phase I is called the “PID phase,” and phase II is called the “control law phase.” Only the phase I flight test plan is discussed. The phase I flight test plan objective is to acquire data to understand fundamental AAW technical issues. Fundamental technical issues, which are important in the validation of AAW technology, involve a wide variety of aerodynamic issues, structural characteristics, and aircraft maneuvering performance. The flight research program strives to address and characterize as many of the flight research issues as is practical.

Aerodynamic issues, which must be understood, include full-scale Reynolds number, Mach, and nonlinear effects. These nonlinear effects can include flow separation and transonic shock effects. In addition, flight test–determined aerodynamic model data must be correlated with available wind-tunnel and aerodynamic performance predictions.

Among the structural characteristics to be evaluated are the time-dependent aeroelastic twist and bending responses of the wing and associated strain fields caused by aerodynamic forces, control forces, and high-*g* maneuvers. Wing aeroelastic characteristics must be correlated with aeroelastic predictions. Wing twist hysteresis must be assessed. The adverse effects of elastic mode coupling with flight control rigid-body control loops must be minimized. The structures data obtained from flight tests also are used to validate the ASE and flutter models.

Aircraft maneuvering performance in terms of roll, yaw, and pitch rates must be measured, especially as these rates change at high dynamic pressures. Control inputs, surface deflections, flight loads, and frequency responses for each control surface are used in conjunction with ground measurements for improved simulation modeling. The flights provide data to help understand how and where control reversal occurs for the AAW aircraft. The flights also provide data to evaluate the individual control surface effectiveness for roll control. The FCS modeling issues all must be addressed prior to application of AAW technology to a new configuration.

To establish realistic design guidance, the AAW flight tests must investigate critical design parameters and develop sufficient knowledge of full-scale aircraft responses. A wind-tunnel model program will complement the flight test program and provide scaled wind-tunnel data with which to correlate flight test data and analysis. The ability to analytically model an active aeroelastic wing is critical to transition the technology to future aircraft. The succeeding paragraphs outline the data that will be acquired during the phase I flight test plan.

The phase I flight tests verify the baseline F/A-18 control laws ability to fly the aircraft; verify core FCC software functions; and perform loads verification, flutter and ASE envelope clearance, airdata calibration, and PID flights. A series of functional check flights (FCFs) precede every research flight to ensure that aircraft and instrumentation systems are functioning. Also during phase I, a failure scenario evaluation has been conducted to verify that sufficient control power exists to fly the F/A-18 aircraft at approach speeds with one leading edge outboard control surface failed while deflected up.

The phase I flight test plan includes testing in the subsonic, transonic, and supersonic flight envelopes (fig. 14). The order of operations (fig. 15) occurs in three blocks in both the subsonic and supersonic flight envelopes. The objectives of block 1 are to perform flutter and ASE envelope clearance; perform aircraft FCFs; perform aircraft maneuvering checkouts; and investigate aircraft handling qualities during simulated outboard LEF failures. The objective of block 2 is to perform airdata calibration. The objectives of block 3 are to perform OBES PID and loads model verification.

The FCFs are conducted to ensure that all aircraft systems are functional, all instrumentation is working properly, and critical FCC downlinks are functional. The flutter clearance verifies that the flutter and aeroservoelasticity margins are acceptable.

To investigate the handling qualities of an aircraft with a failed flap, a test that simulates this failure has been designed and conducted. During this maneuver, the outboard LEF was failed to 3°, 6°, and 10° up. The aircraft then slowed down and the handling qualities were evaluated. Figure 16 shows the aircraft in flight with the simulated failed outboard LEF.

The aircraft maneuvering checkout consists of a set of standardized phasing maneuvers and integrated test block (ITB) maneuvers. The standardized phasing maneuvers are performed at the beginning of each flight throughout the flight test program. The phasing maneuvers include a bank-to-bank roll, a 20° pitch up, a 3-*g* turn, and a steady heading sideslip. These maneuvers provide a check and standardization of all instrumentation parameters in the control room at the beginning of each flight throughout the program. Aircraft maneuvering ITBs are accomplished at selected test points throughout the flight envelopes. The ITB consists of six maneuvers:

1. Reversion check from RFCS to basic F/A-18 system
2. 15° bank-to-bank, 1/4-stick deflection rolls
3. 30° to 45° bank-to-bank, 1/2 to 3/4-stick deflection rolls
4. 90° bank-and-return, full-stick deflection rolls
5. 360° 1/2-stick deflection rolls
6. 390° full-stick deflection rolls

This set of maneuvers allows the research engineers to evaluate the AAW handling qualities and the interaction between the flexible wing and the control system.

Flutter clearance consists of increasing dynamic pressure points. At each test point, Schroeder sweeps (the same sweeps as those performed in the SMI tests) are performed. The response of the aircraft is monitored on strip charts, and assessments of the stability of the aircraft are made in real time.

Block 2 consists of airdata calibration flights. The airdata calibration flights calibrate the pitot-static and flow angle measurement systems and quantify errors so that accurate measurements of Mach number, aircraft velocity, and angle of attack and sideslip are made during flight tests.

Block 3 consists of the PID flights using the OBES. The PID flights are necessary for the success of the AAW flight test program, because they update the existing aerodynamic database, eliminate aerodynamic database deficiencies, and improve the current loads database. This data will be used to refine the analytical models that are used to develop the final set of AAW control laws.

The existing aerodynamic database is not a product of extensive PID testing and analysis. The simulation based on this database generally agrees with previous flight test results; however, individual control surface effectiveness is not well defined for large control surface deflections or for increasing alpha. This difference is important when the control laws are changed, as is planned in the AAW program. To exploit the full differential travel of the outboard LEF, some symmetrically biased control surface deployment might be required to meet component load constraints. The existing database does not support symmetrically biased control surface deflection at high speed. Individual control surface effectiveness for the AAW aerodynamic database is identified through doublet maneuvers. The doublet maneuvers are performed using the OBES for each control surface. The OBES doublet maneuvers last approximately 30 seconds (fig. 17). Each surface goes through a positive deflection followed by a negative deflection in approximately 3 seconds. The surfaces are strung together in one maneuver for flight test efficiency. Data from these maneuvers are then used in loads[16] and aerodynamics[17] model development.

In addition to the OBES PID maneuvers, three additional piloted maneuvers are flown at each test point using the standard flight controls. The additional maneuvers are required to evaluate the linearity assumed in the loads model derived from the PID maneuvers, which had produced only low load level inputs. The loads model verification maneuvers include a 360° roll, a 5-*g* wind-up turn, and a 4-*g* rolling pullout. Data from these maneuvers might yield loads model modifications required for improved accuracy at high load levels. The maneuvers are approached in a buildup fashion using partial control inputs with respect to those required.

FLIGHT TEST STATUS AND OBSERVATIONS

At the end of January 2003, the AAW aircraft had successfully flown 11 research missions. The flutter clearance FCFs, and airdata calibration maneuvers have been completed through the subsonic envelope. The aircraft maneuvering test points are approximately 91-percent complete. The OBES PID is approximately 36-percent complete with 42 test points remaining. The loads model verification has 79 maneuvers in the plan, and only 16 have been completed.

The failure scenario evaluation was conducted to verify that sufficient control power exists to fly the F/A-18 aircraft at approach speeds with one leading edge outboard control surface failed while deflected up. After the flap was positioned 10° up through an OBES command, the pilot slowed down to landing speeds that increased the angle of attack on the aircraft. At a low Mach number of approximately 0.35, the aircraft passed through 10 degrees of angle of attack, at which point the aircraft experienced an abrupt wing stall event, causing a steep bank angle (fig. 18). The abrupt wing stall was recoverable and very repeatable. By performing this maneuver, the AAW flight test team is better able to define emergency procedures during an LEF failure.

The ITB that has been completed has shown no adverse handling qualities resulting from the AAW aircraft modifications. During some of these maneuvers, however, the AAW aircraft approached and sometimes exceeded the established component load limits. These high loads have been observed during full-stick rolls and 4-*g* rolling pullouts on the trailing edge flap and aileron hinge moments and on the wing fold and root loads. Data from a previously flown F/A-18 loads aircraft showed that the AAW aircraft can exceed the load limits at some of the test points. The AAW aircraft seems to exceed the load limits during more benign maneuvers than those of the previous aircraft. During one maneuver, the aileron exceeded 110 percent of the load limit during a 4-*g* rolling pullout. The data from the previously flown aircraft showed a similar high load, but the high load occurred during a 6-*g* rolling pullout.

Visual video recordings of the wing indicate that the wing is flexible and twists during planned maneuvers. Individual and combined surface contributions to the wing twist are being evaluated based on the data that have been completed. Also, the flexibility of the aileron can be visually observed. The inboard section of the aileron is deflected more than the outboard section. The inboard section is where the actuator pushes on the surface. This effect can influence the ability of the aileron surface to control wing flexibility.

SUMMARY

The Active Aeroelastic Wing (AAW) technology is a multidisciplinary, synergistic technology that integrates air vehicle aerodynamics, active controls, and structures advanced technology to maximize air vehicle performance. The concept uses wing aeroelastic flexibility for a net benefit and enables the use of wings that are aeroelastically deformed into shapes for optimal performance. The technology takes advantage of high aspect ratio, thin, swept wings on fighter aircraft.

The AAW Flight Research Program started with a full-scale F/A-18 aircraft that was modified. The aft wing box panels were changed to decrease the torsional stiffness of the wing for AAW technology. A new leading edge flap drive system was added, which increased the performance of the outboard leading edge flap. Modifications made to the flight control computers include the addition of software, such as the onboard excitation system, which provides precise inputs to the control surfaces needed for the parameter identification efforts in loads and aerodynamics. An extensive research instrumentation system was implemented on the AAW aircraft, which includes more than 1600 individual measurements. The modifications made to the aircraft resulted in an aircraft with added flexibility for AAW flight research.

The AAW flight research testing has been planned in two phases that ensure a safe and thorough evaluation of AAW technology. The 11 flights of the AAW aircraft conducted through January 2003 have shown that the aircraft is an effective test bed. Although the flight test results are preliminary, the higher loads from smaller inputs are starting to show the effects of the added flexibility.

Through May 2003, the AAW program will continue to fly the phase I flight profiles through the supersonic envelope. Analysis of the phase I data will emphasize the development of aerodynamic and loads databases that will be used for AAW control law development.[18]

Phase II of the AAW Flight Research Program will modify the control laws to demonstrate AAW technology. The goal of the AAW control laws is to maximize performance using the wing flexibility. The baseline F/A-18 aircraft uses the entire leading edge flap, inboard trailing edge control surface, and 15° differential stabilator to roll the aircraft above Mach 0.6. The AAW aircraft will use all the wing leading and trailing edge controls, but will not incorporate the differential deflection of the tail for roll. This method is deliberately used so that the AAW experiment can clearly demonstrate the effects of wing control power, exclusive of other effects. The challenge for the control law design is to maximize roll performance, while preventing the aircraft wing loads from exceeding the established limits.

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FIGURES

Figure 1. The Active Aeroelastic Wing aircraft.

Figure 2. Location of the aft upper wing cover panels.

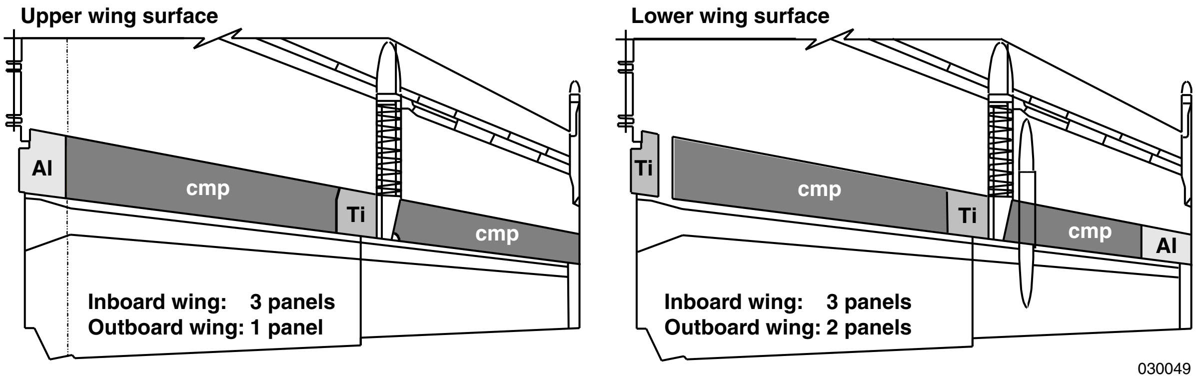

Figure 3. Original aircraft panel configuration.

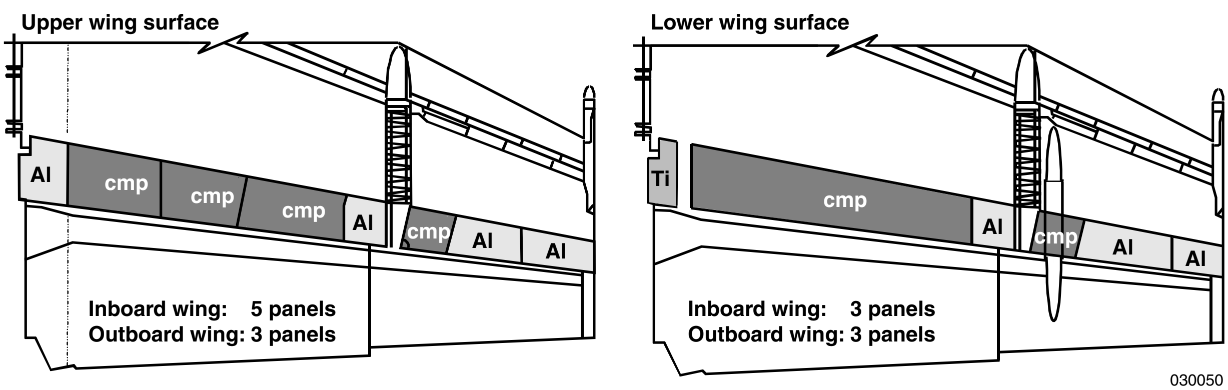

Figure 4. Modified AAW aircraft wing panel configuration.

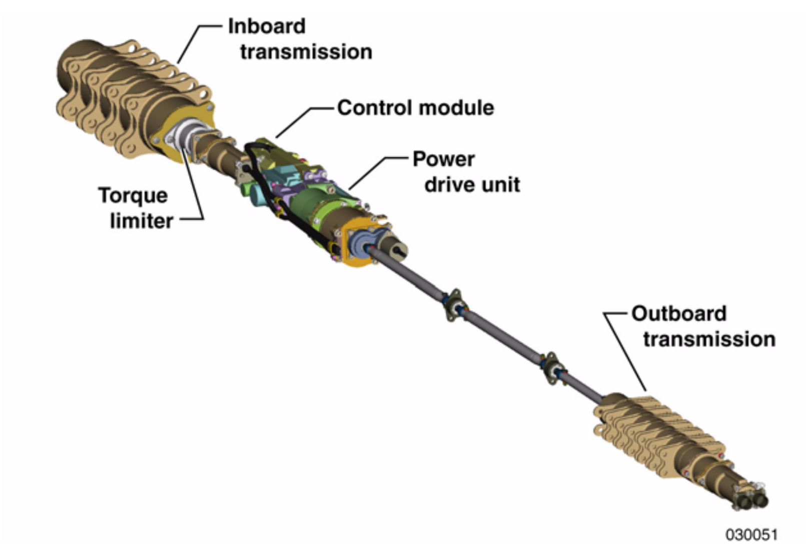

Figure 5. Leading edge flap drive system.

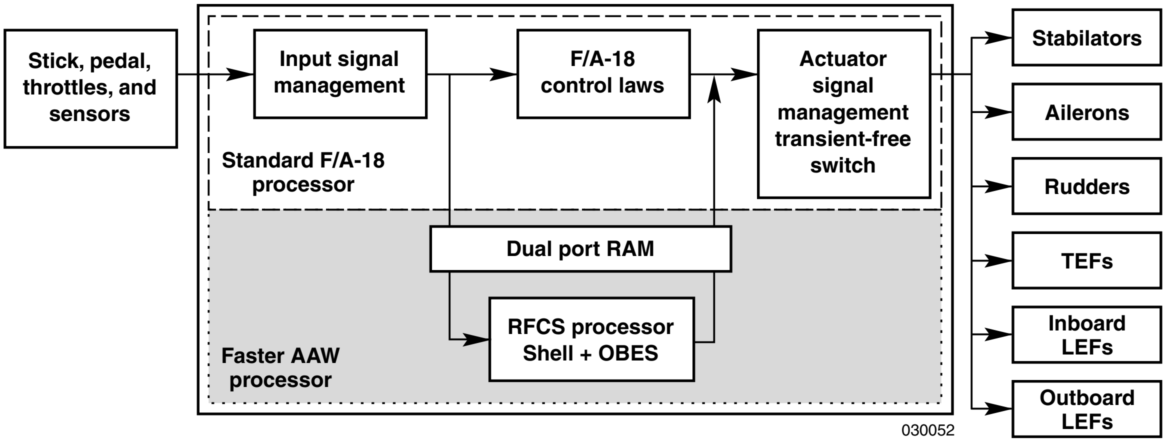

Figure 6. AAW flight control computer architecture.

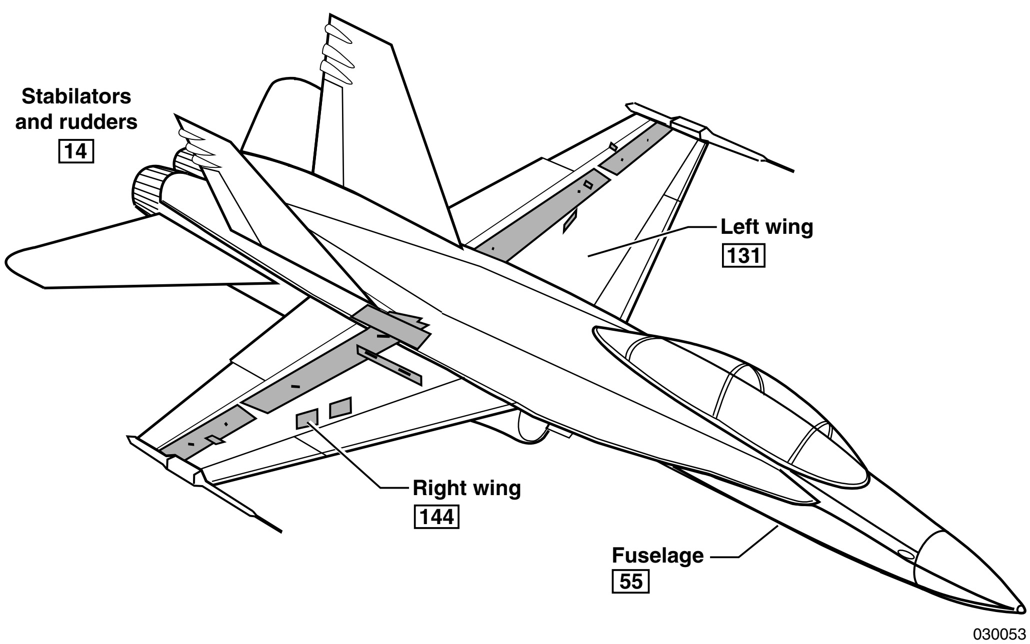

Figure 7. AAW instrumentation sensor numbers.

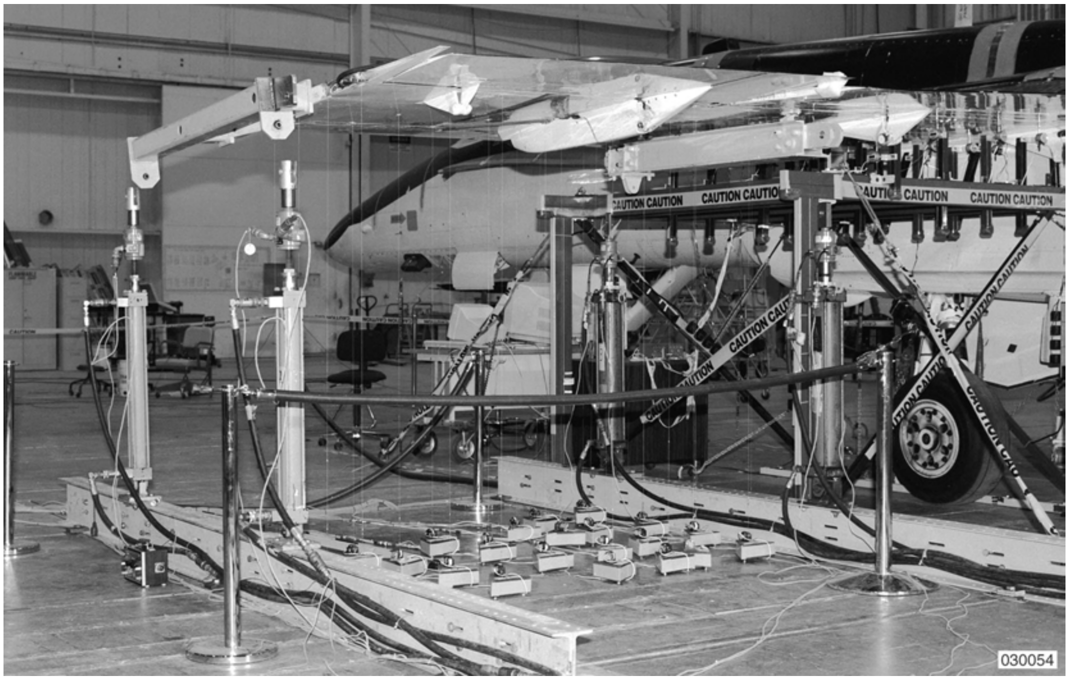

Figure 8. AAW F/A-18 wing stiffness test.

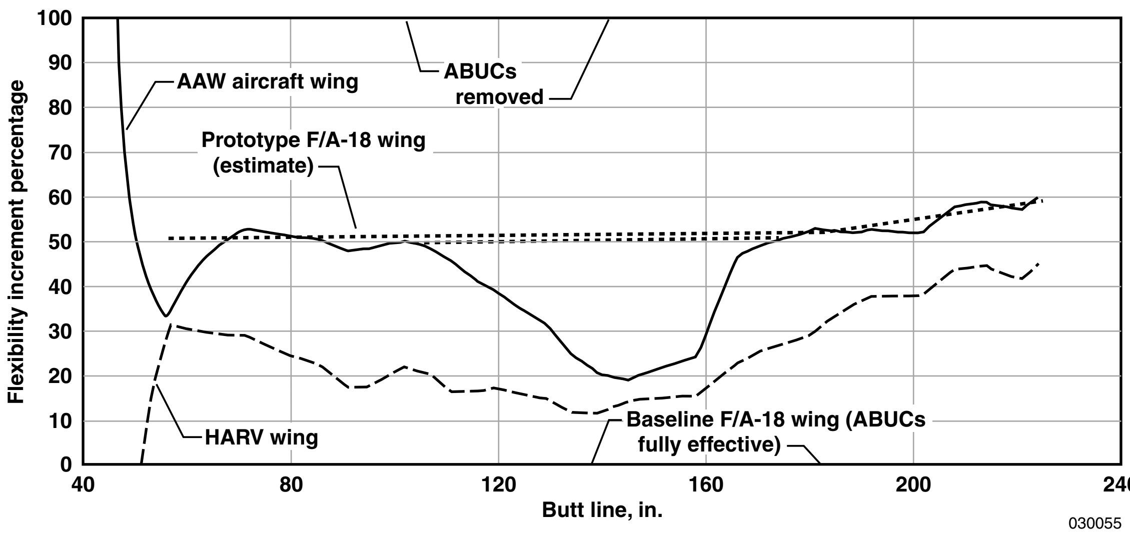

Figure 9. Comparison of wing flexibility between AAW research F/A-18 aircraft and baseline F/A-18 aircraft.

Figure 10. AAW aircraft undergoing loads calibration testing.

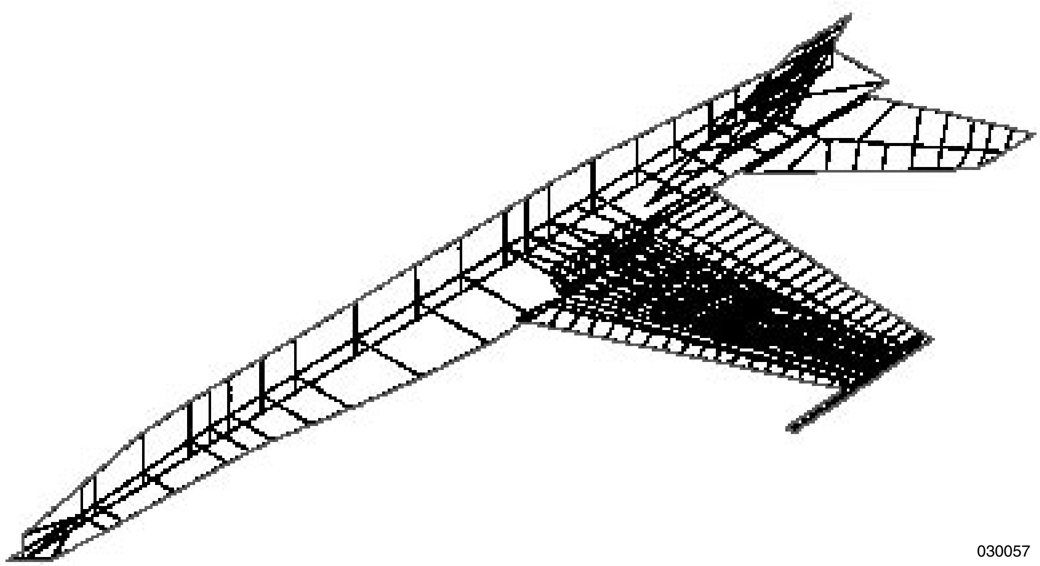

Figure 11. Finite element model.

Figure 12. AAW aircraft on the soft support system for testing.

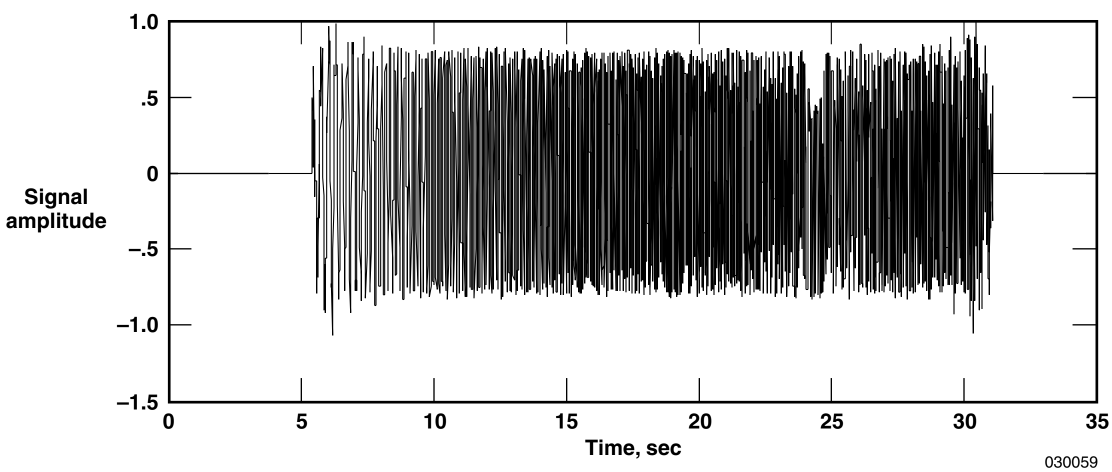

Figure 13. Structural mode interaction OBES Schroeder sweep.

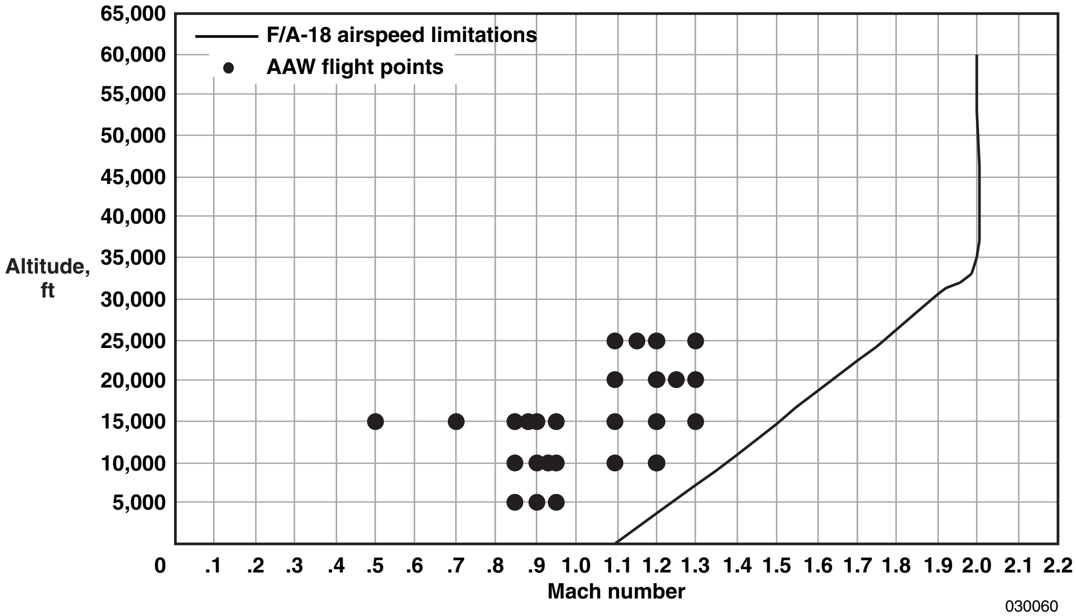

Figure 14. AAW flight envelopes.

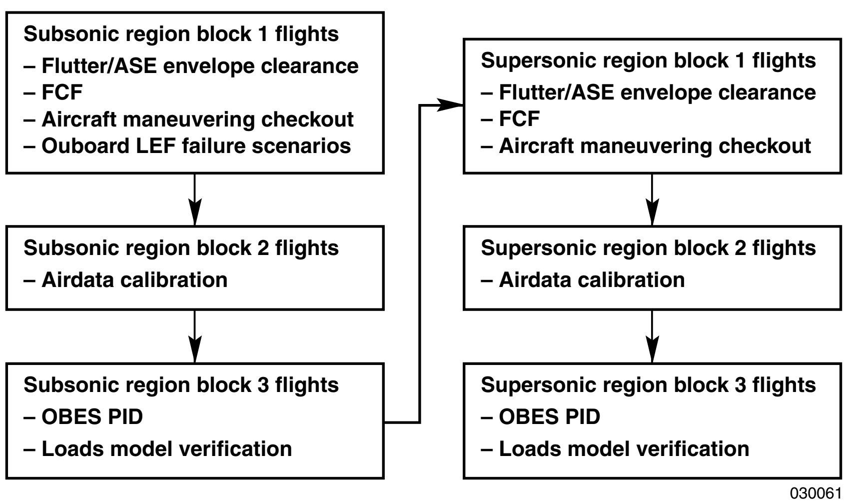

Figure 15. AAW phase I flight test order of operations.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (Leave blank)

2. REPORT DATE
April 2003

3. REPORT TYPE AND DATES COVERED
Technical Memorandum

4. TITLE AND SUBTITLE
The Active Aeroelastic Wing Phase I Flight Research Through January 2003

5. FUNDING NUMBERS
WU 710 61 14 SE 14 00 AAW

6. AUTHOR(S)
David Voracek, Ed Pendleton, Dr. Kenneth Griffin, Eric Reichenbach, and Leslie Welch

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
NASA Dryden Flight Research Center
P.O. Box 273
Edwards, California 93523-0273

8. PERFORMING ORGANIZATION REPORT NUMBER
H-2521

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
Washington, DC 20546-0001

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
NASA/TM-2003-210741

11. SUPPLEMENTARY NOTES
Presented at the Applied Vehicle Technology Panel (AVT), Symposium on "Novel and Emerging Vehicle and Vehicle Technology Concepts," Brussels, Belgium, April 7–9, 2003, AVT-99/RYS-014.

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified—Unlimited
Subject Category 05

This report is available at http://www.dfrc.nasa.gov/DTRS/

12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

This report describes the technical content of the Active Aeroelastic Wing (AAW) Flight Research Program and discusses the analytical development, aircraft test bed modifications, ground test results, and flight research results through January 2003. The goals of the AAW Flight Research Program are to demonstrate, in full scale, AAW technology, and to measure the aerodynamic, structural, and flight control characteristics associated with the AAW aircraft. Design guidance, derived from the results of this benchmark flight program, will be provided for implementation on future aircraft designs.

14. SUBJECT TERMS
Active aeroelastic wing, Aeroelasticity, Flight research, Morphing, Structures

15. NUMBER OF PAGES
25

16. PRICE CODE
A03

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	Unlimited